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PERCEPTUAL DIMENSIONS OF SIMULATED SCENES RELEVANT FOR VISUAL LOW-ALTITUDE FLIGHT

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This report has been reviewed and is approved for publication.

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Previous experiments using multidimensional scaling reveal that pilots flying at low altitudes perceive two types of detail in real-world scenes: (a) hills and ridges, and (b) discrete scene elements exemplified by large objects or groups of objects. The present experiments sought to determine the extent to which these types of detail can be effectively rendered in computer-generated flight simulator scenes. In Experiment 1, subjects rated the visual similarity between simulated scenes exhibiting a range of different features. Ratings were analyzed with multidimensional scaling which revealed that subjects perceived variation in three types of detail: (a) texture on the terrain, (b) objects, and (c) hills. Evidence for a dimension related to texture on the terrain arose from comparisons involving completely featureless surfaces which were not represented in real-world scenes. Field of view was reduced in Experiment 2 and results revealed a change in perceived detail. Texture, objects, and hills were perceived in scenes, but they were perceived as being a single type of detail contributing to global scene complexity. Taken together, present results indicate that detail important in real-world scenes can be effectively rendered in simulated scenes. Indeed, present scenes exhibited an even richer variety of detail than real-world scenes used previously. Nevertheless, what is important in scenes is not directly related to specific scene features but to more abstract forms of information mediated by those features.

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PREFACE

This effort was conducted at the Armstrong Laboratory, Aircrew Training Research Division (AL/HRA), in Mesa, AZ in support of training research and development to maintain air combat readiness and visual scene and display requirements.

This work was performed by the University of Dayton Research Institute (UDRI) in support of Work Unit No. 1123-32-03, Tactical Scene Content Requirements, Principal Investigator, Dr. Elizabeth L. Martin, and 1123-03-85, Flying Training Research Support, Contract No. F33615-90-C-0005. Contract Monitor was Ms. Patricia A. Spears. One of the objectives of these work units is to identify flight simulator visual scene content factors that contribute to training effectiveness for low-altitude flight.

The author wishes to thank Dr. Elizabeth L. Martin for helpful comments on an earlier draft of this report and Ms Marge Keslin (UDRI), who oversaw final editing.

PERCEPTUAL DIMENSIONS OF SIMULATED SCENES RELEVANT FOR VISUAL LOW-ALTITUDE FLIGHT

INTRODUCTION

When designing a computer-generated scene for use in a flight simulator, or any vehicle simulator for that matter, it is widely recognized that there must be some minimum level of scene complexity to support tasks involving visually guided motion within the environment. One approach to specifying the type and quantity of scene elements required for simulating such tasks is to take as a starting point a completely flat and featureless terrain surface and then examine the influence on task performance of adding various elements to scenes. Examples of this approach are widely represented in the literature (Barfield, Rosenberg & Kraft, 1989; Buckland, Edwards & Stevens, 1981; Buckland, Monroe & Mehrer, 1980; DeMaio, Rinalducci, Brooks & Brunderman, 1983; Lintern & Koonce, 1991; Lintern, Thomley-Yates, Nelson & Roscoe, 1987; Lintern & Walker, 1991; Martin & Rinalducci, 1983; McCormick, Smith, Lewandowski, Preskar & Martin, 1983). An alternative approach is to take as a starting point the real-world environment and then inquire as to which specific scene properties are relevant in that context. The advantage of such an approach is that it provides the possibility of identifying relevant scene properties that have either not yet been hypothesized to be important or cannot yet be modeled in computer-generated scenes due to technological limitations.

Kleiss (1990, in press) undertook an analysis of real-world scenes using multidimensional scaling (MDS). The task of interest was low-altitude flight and the stimuli were videotape segments depicting low-altitude, high-speed flight over a variety of real-world terrains. Results revealed that pilots perceived variation in two relevant scene properties: (a) terrain shape mediated by presence or absence of hills and (b) discrete objects exemplified by large buildings or groups of trees. These results suggest that efforts to design scenes for simulating low-altitude flight should focus specifically in these two types of scene properties. However, these results also provide a criterion by which to assess the content of simulated scenes. Specifically, if scene properties found to be relevant in real-world scenes can be represented with adequate perceptual fidelity in flight simulators, then an MDS analysis of simulated scenes should reveal a dimensional structure similar to that obtained with real-world scenes. Deviations with respect to the number, type, or relative importance of dimensions will indicate specific discrepancies. The purpose of the present experiments is to assess the perceived structure of computer-generated scenes intended to exhibit scene properties found to be relevant in real-world scenes.

EXPERIMENT 1

Method

Subjects

The subjects were five male U.S. Air Force and Navy pilots (mean age was 43.6 yr and mean military flying time was 2580 hr), five male and five female nonpilots (mean age 34 and 30.6 yr respectively). Pilots were not currently on flying status but had previous experience flying jet-fighter aircraft at low altitudes. A heterogeneous sample was used to take advantage of individual differences information provided by the MDS algorithm used in this experiment.

Apparatus

Scenes were generated by the Advanced Visual Technology System (AVTS) (see Eibeck & Petrie, 1988 for specifications). Among its capabilities is cell texturing, a technique by which a complex digitized pattern is rendered on a surface by modulating the lightness and darkness of the surface. Imagery was back-projected using three Barco CRT projectors onto three pentagonal screens arrayed horizontally within a dodecahedral frame. Maximum addressable resolution for each of the three channels was 1,000 lines by 1,000 elements/line. Each screen measured 1.75 m horizontally by 1.32 m vertically providing a maximum view of approximately 210 deg horizontally by 100 deg vertically measured from a viewing distance of 1 m. Subjects were seated in a jet-fighter simulator cockpit with no functioning instruments or controls.

Stimuli, Design and Materials

Stimuli were 5 s segments of straight-and-level flight through computer-generated scenes exhibiting a variety of scene properties. Speed was constant at 450 kn and altitude was constant at 150 ft above the highest point in the scene; i.e., when hills were present, altitude was 150 ft above the tops of the hills. These values are typical of jet-fighter aircraft during combat missions.

Scenes exhibited four types of terrain shape: (a) flat, (b) rolling, (c) sparse hills, or (d) dense hills. Rolling terrain, sparse hills, and dense hills each comprised hills that extended vertically 65-75 ft. The tops of hills were diamond-shaped plateaus measuring 75 ft in the direction of travel and 150 ft perpendicular to the direction of travel. The sides of hills in rolling terrain sloped upward about 4 deg from horizontal. The average center-to-center spacing of hills was about 2400 ft. Adjacent hills were joined such that no flat terrain was visible between them. The sides of sparse hills and dense hills sloped upward about 13 deg from horizontal. Average center-to-center spacing of dense hills was about 800 ft. Adjacent hills were joined such that no flat terrain was visible between them. Terrain with sparse hills was made by removing approximately 60% of the hills from terrain with dense hills and replacing them with flat terrain.

Scenes exhibited four types of scene elements on the terrain: (a) untextured terrain polygons with no trees, (b) textured terrain with no trees, (c) textured terrain with evenly spaced trees, or (d) textured terrain with grouped trees. Untextured polygons defining flat terrain were a uniform and undifferentiated shade of green with a luminance of 1.555 Cd/m^2. Untextured polygons defining rolling terrain, sparse hills, and dense hills exhibited subtle luminance differences to enhance contrast. The sides of hills were the same shade of green as untextured flat terrain. The tops of hills were highest in luminance (2.354 Cd/m^2) whereas intervening flat terrain, when present, was an intermediate level of luminance (1.939 Cd/m^2). AVTS also uses a shading algorithm which subtly varies the luminance of surfaces depending on their orientation in relation to the simulated sun. Texture consisted of an irregular pattern of blotches exhibiting approximately the same three luminances as described above. Mean luminance of texture sampled across a range of texture luminance values was 2.001 Cd/m^2. Trees were made by applying a digitized image of a 35-ft-tall pine tree to object surfaces. Mean luminance of trees sampled across a range of texture luminance values was 0.637 Cd/m^2. Figure 1 shows a photograph of a scene with flat terrain, texture and grouped trees viewed from the cockpit of the simulator.

The four types of terrain shape were crossed with the four types of scene elements yielding 16 unique scenes. Sixteen stimuli yield a total of 120 unique stimulus pairings. Due to time constraints, an incomplete data design was used in which each subject viewed only half (60) of the 120 possible stimulus pairs (see Schiffman, Reynolds & Young, 1981). MacCallum (1978) provides evidence that structure can be successfully recovered from data with as many as 60% missing observations so long as sample size is moderately large (greater than 10), random error is low, and different observations are missing across subjects. The 120 possible scene pairs were randomly divided into two subsets with the following constraints: (a) that individual scenes appeared about equally often in each subset, (b) that individual scenes appeared about equally often as the first and second elements of a pair, and (c) that no scene appeared in consecutive pairs. Two additional subsets were created in a similar fashion except that the order of scenes within each pair was reversed.

Following Schiffman, et al. (1981), similarity judgments were recorded on 120-mm, ungraduated lines anchored at the left with "Same" and at the right with "Different." Rating scales were arranged in a booklet containing four scales per page, each numbered in sequence.

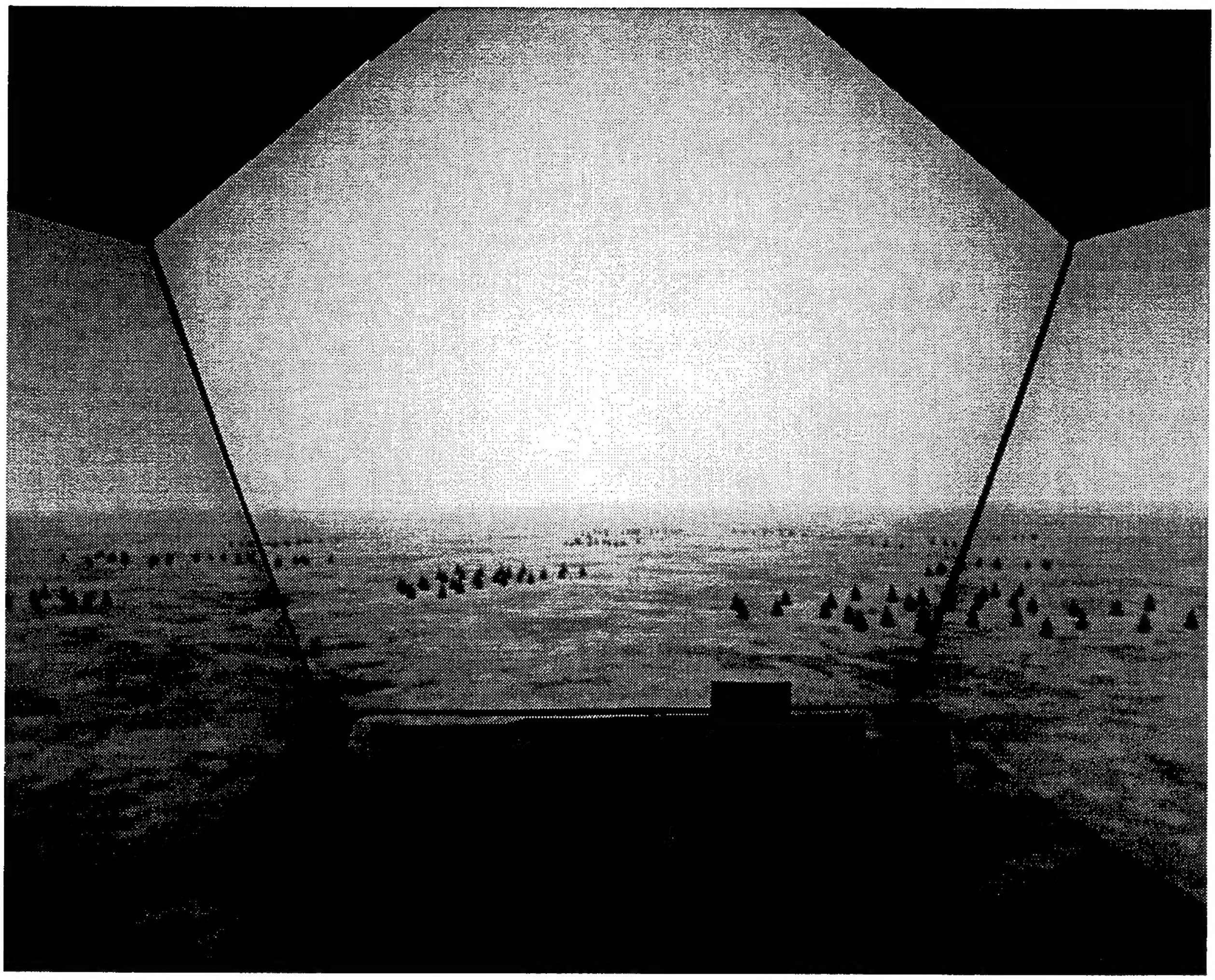


Figure 1.
Scene with Flat Terrain and Grouped Trees.

Procedure

Subjects were informed that the purpose of the experiment was to investigate flight simulator visual scene properties useful for perceiving and controlling flight at low altitudes. They were told that they would be viewing short segments of flight through a variety of simulated scenes and would then make judgments as to how similar the two scenes looked with respect to visual cues. Stimuli were presented sequentially in pairs with a pause of 2-4 s between segments. Subjects were asked to imagine that they were actually piloting the aircraft through each scene and then to rate the extent to which the second scene in each pair looked the same or different than the first with respect to visual motion. If the two scenes looked the same, a mark was to be placed at the extreme left end of the rating scale. If the two scenes looked different, a mark was to be placed somewhere along the line indicating how different. Subjects were encouraged to base their judgments on a general impression of similarity rather than attempting to identify specific scene properties that they felt were important. They were also encouraged to use the entire range available on rating scales. To familiarize subjects with the range of scene elements depicted in scenes, each scene was first shown individually before presentation of stimulus pairs. Subjects were informed that speed would be constant at 450 kn and altitude would be constant at 150 ft above the highest point in the scene. It was explained that two scenes in a given pair would never be exactly identical but that individual scenes would be repeated in different pairs. Approximately equal numbers of subjects viewed each of the four subsets of stimuli.

Each trial began with a uniform gray display field which remained visible until the subject pressed a button to initiate onset of the first scene in the stimulus pair. Scenes within each pair were separated by a uniform blue display field which remained visible for about 2 s. Following presentation of the second scene in a given pair, the gray display field reappeared and remained visible until the subject initiated the next trial.

Results

Data were distances in millimeters measured from the left end of each scale to the point at which the subject marked the scale. The maximum range of values was 0 to 120 with larger values indicating greater dissimilarity. Rating data were submitted to a multidimensional scaling analysis using ALSCAL for PCs (Young, Takane & Lewyckyj, 1978). A weighted (individual differences) approach was used because: (a) it generally yields the most robust and reliable results, (b) spatial configurations are fixed in relation to dimensional axes and are directly interpretable without axis rotation, and (c) information is provided regarding possible individual differences among subjects with regard to the relative weighting of dimensions (Schiffman, et al., 1981). Ratings were assumed to be ordinal and continuous. Missing stimulus pairs were treated as missing values.

Three measures describe the discrepancy between dissimilarities derived from rating data and corresponding interstimulus distances in MDS spatial configurations of various dimensionalities: Stress (Kruskal & Wish, 1978), S-Stress (Takane, Young & de Leeuw, 1977), and 1-RSQ. Stress is based upon MDS distances, S-Stress is based upon squared MDS distances, and 1-RSQ is the proportion of variance in dissimilarities not accounted for by a regression of dissimilarities onto MDS distances. Smaller values indicate better fit for all three measures. Figure 2 shows S-Stress, 1-RSQ, and Stress as a function of increasing dimensionality. ALSCAL does not compute a one-dimensional solution with the individual differences approach. A common criterion for identifying correct dimensionality is the occurrence of an "elbow" at a particular dimensionality (e.g., Kruskal & Wish, 1978). There is no strong evidence of an elbow for the Stress measure. However, an elbow is clearly indicated at dimensionality equal to three for 1-RSQ. Also, there is hint of an elbow at dimensionality equal to three for S-Stress. The three-dimensional solution will, therefore, be considered.

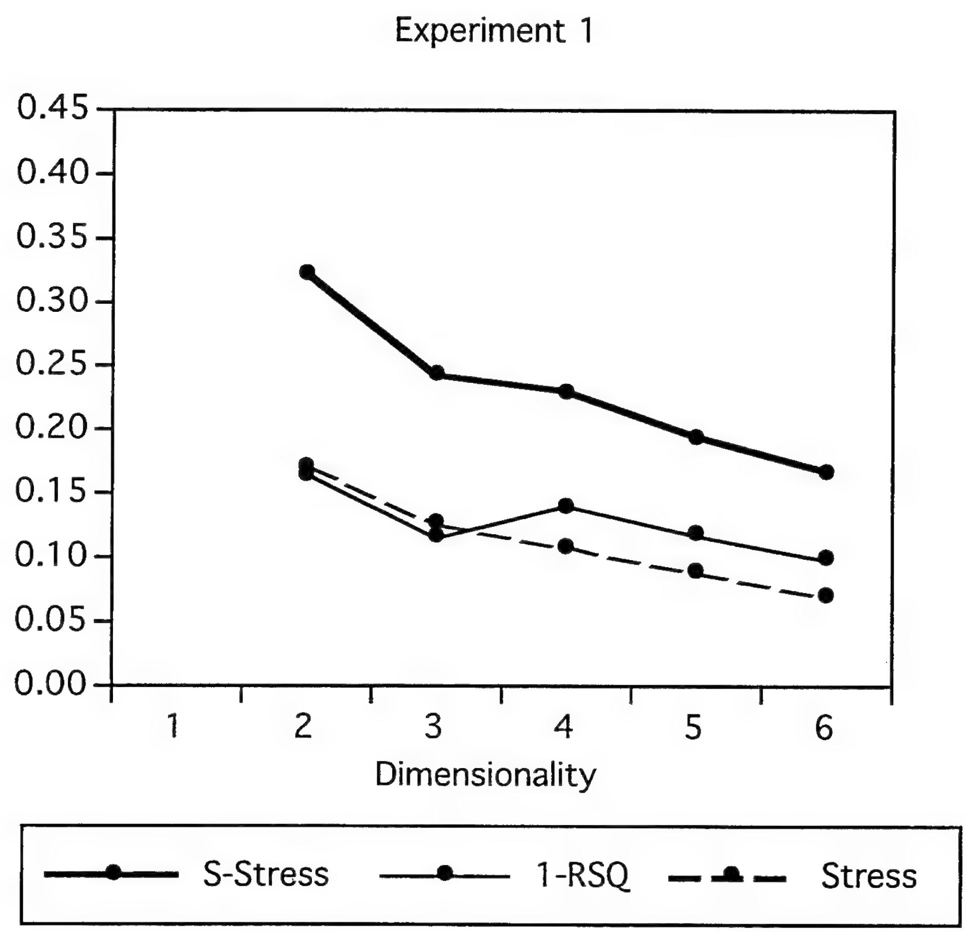


Figure 2.
S-Stress, 1-RSQ and Stress as a Function of Dimensionality: Experiment 1.

A feature of ALSCAL output provided with the individual differences option is subject weights which reflect the relative importance of each dimension for individual subjects. The extent to which the weighting of dimensions for a given subject is proportional to the group is indexed by "weirdness." A weirdness value near one indicates one large weight and the others small. A weirdness value near zero indicates that weights are exactly proportional to the group. Squared subject weights sum to RSQ for individual subjects. When averaged across subjects, squared subject weights provide estimates of variance explained by each dimension for the group. These must be taken as estimates because the data are assumed to be ordinal in nature and do not satisfy the metric assumptions underlying usual interpretations of variance. Table 1 shows subject weights and weirdness values for individual subjects plus the average for squared subject weights for each dimension. Note that Dimension 1 explains the largest proportion of variance in similarity ratings and is, therefore, the most important dimension. Dimensions 2 and 3 are relatively equal in group. Squared subject weights sum to RSQ for individual subjects and when averaged across weighting. Subject 11, a female nonpilot, has a relatively large weirdness value reflecting a comparatively large weighting of Dimension 2 and a comparatively small weighting of Dimension 3. However, there is no evidence of systematic differences among subgroups within the sample suggesting that subjects did not differ notably with respect to the particular features that were attended in scenes.

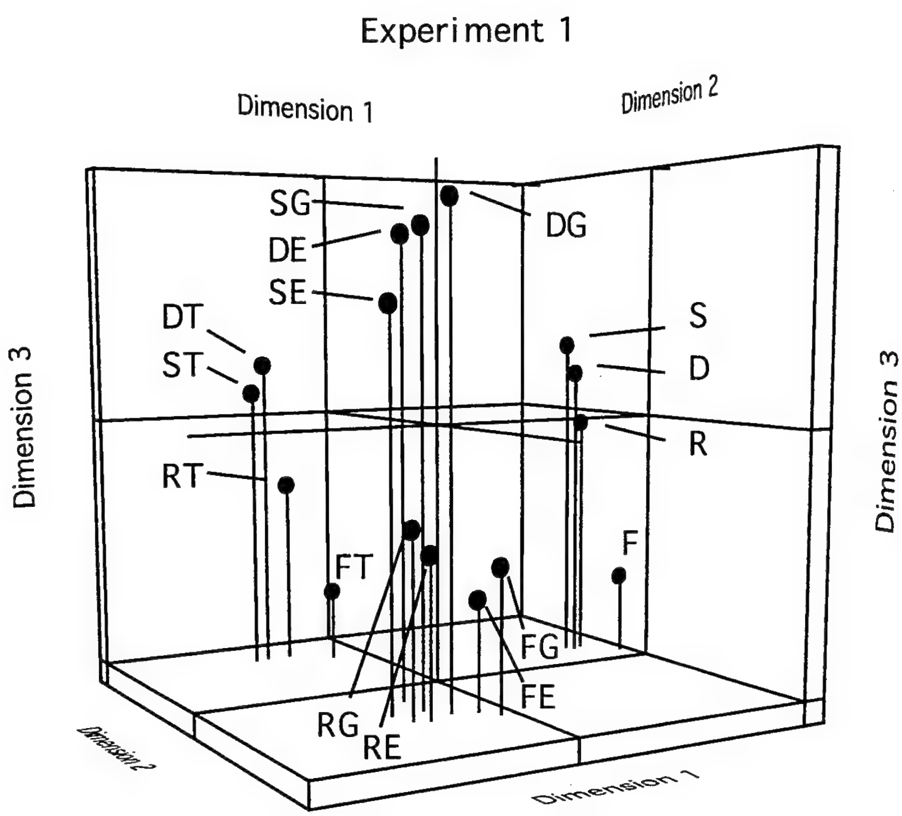
Table 1. Subject Weights and Weirdness Values for Individual Subjects Plus Average Squared Subject Weights for Each Dimension: Experiment 1.

	Subject Weights			
Subject	Dimension 1	Dimension 2	Dimension 3	Weirdness
Fighter Pilots				
1	0.577	0.633	0.484	0.151
2	0.774	0.270	0.447	0.314
3	0.649	0.562	0.477	0.059
4	0.606	0.381	0.457	0.103
5	0.646	0.625	0.384	0.190
Male Nonpilots				
6	0.405	0.487	0.741	0.356
7	0.713	0.252	0.403	0.311
8	0.630	0.268	0.617	0.331
9	0.595	0.405	0.608	0.195
10	0.670	0.489	0.488	0.030
Female Nonpilots				
11	0.651	0.730	0.122	0.525
12	0.541	0.665	0.411	0.231
13	0.437	0.561	0.593	0.239
14	0.627	0.562	0.358	0.173
15	0.754	0.374	0.434	0.197
Average Squared Subject Weights	0.392	0.256	0.238	

Figure 3 shows the derived three-dimensional spatial configuration. Codes for various scene conditions are listed below the spatial configuration. Dimensions 1 and 2 define the horizontal plane and Dimension 3 defines the vertical axis. It is immediately apparent that scenes cluster into three groups in relation to the horizontal plane. One contains scenes with no texture or trees, one contains scenes with texture alone, and one contains scenes with texture as well as trees. Considering Dimension 1 first, scenes with no texture or trees are positioned at the extreme right side of the spatial configuration whereas remaining scenes are positioned nearer the left side of the spatial configuration. Note that scenes with trees are positioned about equally in relation to the Dimension 1 axis as scenes with texture alone, arguing that trees do not add appreciably to the information already provided by texture on the terrain. This pattern supports an interpretation of this dimension consistent with presence or absence of texture on the terrain.

Scenes nearest the end of Dimension 2 at the back of the spatial configuration contain texture and no trees whereas scenes nearest the other end of Dimension 2 at the front of the spatial configuration contain texture plus trees. Scenes with no texture or trees are positioned at the middle of the Dimension 2 axis suggesting a qualitative distinction between texture on the terrain versus trees. There is no evidence of a difference between scenes with evenly spaced trees and scenes with grouped trees, arguing that grouping is not an important factor related to this dimension.

Scenes nearest the end of Dimension 3 at the top of the spatial configuration contain steeply sloped hills as well as trees, whereas scenes near the other end of Dimension 3 at the bottom of the spatial configuration contain flat terrain. Proceeding upward from the bottom of the spatial configuration one first encounters scenes with rolling terrain and then scenes with steeply sloped hills, but no trees. This pattern supports a general interpretation of Dimension 3 consistent with variation in terrain shape mediated by the slope of hills. It would appear the trees facilitate perception of steeply sloped hills as scenes with this combination of factors form an additional cluster distinct from other scenes. Two other patterns are evident within this cluster. Scenes with grouped trees are, on average, positioned nearer the top of the Dimension 3 axis than corresponding scenes with evenly spaced trees. Hence, this configuration of trees may afford a slight advantage for perceiving steeply sloped hills. Also, note that scenes with dense hills are, on average, positioned nearer the top of the Dimension 3 axis than corresponding scenes with sparse hills. Hence, the spacing of hills would also appear to be a factor. There is no advantage for dense hills with scenes containing untextured terrain and this may reflect the higher level of contrast between sparse hills and the lighter background terrain.



F = Flat
R = Rolling
S = Sparse Hills
D = Dense Hills

T = Texture
E = Texture & Evenly Spaced Trees
G = Texture & Grouped Trees

Figure 3.
Three-Dimensional Spatial Configuration: Experiment 1.

Discussion

Present results differ from those obtained previously using real-world imagery (Kleiss, 1990; in press) in that there is evidence for three dimensions in the present experiment rather than just two. Dimension 2, reflecting a property related to trees, and Dimension 3, reflecting terrain shape, are similar to the two dimensions identified previously with images of real-world scenes. Dimension 1, related to presence or absence of texture on the terrain, is unique to this experiment. Dimension 1 was defined by comparisons involving scenes with untextured terrain. Kleiss' (1990; in press) stimulus set contained scenes exhibiting a calm ocean and a dry lake bed, both of which contained very little surface detail. However, these scenes appear to have been sufficiently rich in detail to mask a distinction between textured and untextured surfaces reflected in Dimension 1 of the present experiment. Compared to results obtained with real-world scenes, present results argue for a further subdivision into three unique dimensions.

Scenes with untextured terrain not only served to define texture as a unique property of scenes in Dimension 1, but also defined a qualitative difference between texture and trees in Dimension 2. This difference was not apparent in results of Kleiss (1990; in press) which, using images of real-world scenes, revealed continuous variation in the size and spacing of objects in scenes. Because texture is related to both Dimensions 1 and 2, we may conclude that texture plays a dual role in scenes. Dimension 1 appears to reflect a global property of texture related to the distribution of texture elements on surfaces. Trees appear to stand out as discrete elements in scenes, and we may speculate that the importance of texture in Dimension 2 relates to local properties of individual texture blotches. We cannot be sure what precisely defines the distinction between texture and trees in Dimension 2, but Harker and Jones (1980) discuss a difference between horizontal and vertical scene features which may be pertinent to this discussion. They note that as one approaches to fly over an environmental feature, geometric relations within features as well as between features change in predictably different ways for features aligned horizontally with the terrain surface (e.g., a discoloration on the terrain surface) compared to features that extend vertically above the terrain surface. They suggest that geometric relations specific to the orientation of features (either horizontal or vertical) are differentially informative as to the motion of an aircraft in relation to the terrain. A distinction between features related to vertical extent is also supported by evidence of performance differences between vertical objects and flat (i.e. horizontal) objects with a simulated low-altitude flight task (Martin & Rinalducci, 1983). Clarifying the distinction between texture and trees in Dimension 2 remains a topic for future research.

Kleiss (in press) found that groves of trees were better exemplars of objects than individual trees scattered evenly on the terrain. There was no evidence in Dimension 2 that grouped trees

were perceived differently than evenly spaced trees. Hence, grouping does not appear to be the crucial property exhibited by groves of trees in real-world scenes. Perhaps when trees are spaced closely together they are perceived as a single larger object, in which case size would be the important factor.

Dimension 3 reveals high sensitivity to both the slope and spacing of hills in scenes. The importance of undulating terrain in images of real-world scenes (Kleiss, in press), therefore, reflects a composite of both steep slope and close spacing. Kleiss (in press) found that perception of hills and ridges in real-world scenes was dependent in large part upon presence of motion in scenes and speculated that perception of hills was mediated by optic flow discontinuities between surfaces separated in depth. An important prerequisite for perceiving optic flow discontinuities is high texture density (e.g., Previc, 1989; Stevens, 1994). It is interesting to note that scenes with steeply sloped hills and texture alone are positioned about equally in relation to the Dimension 3 axis (Figure 3) as scenes with steeply-sloped hills and no texture (see Fig. 3). This would seem to eliminate optic flow discontinuities as the basis for perceiving hills in Dimension 3. Recall that Dimension 1 relates to a property of texture distributed globally on the terrain. Optic flow phenomena may therefore be localized in Dimension 1.

Although perception of hills does not appear to be mediated by optic flow phenomena, an argument can still be made that dynamic factors are involved. Consider, for example, Figure 4 which shows a view of the scene with dense hills and grouped trees. Hills are difficult to discern in this photograph despite evidence that they are clearly perceived in dynamic stimulus segments. While image quality may be poorer in this photograph than in the stimulus display, hills are difficult to discern even in the simulator when viewed statically. The implication is that some important information for perceiving hills is dependent upon dynamic stimulus presentation.

In Figure 4 it can be seen that the distribution of trees on the terrain appears to be a cue for the slope of the terrain. The importance of trees in this context may, therefore, relate to relationships among trees which are informative as to the orientation of terrain polygons. The closer spacing of grouped trees may tend to highlight these relationships. It is also possible that trees are occluded by foreground hills such that dynamic occlusion and disocclusion of trees becomes a factor. It is important to note that the advantage for grouped trees in Dimension 3 is unrelated to the advantage for groves of trees in real-world scenes (Kleiss, in press) because trees in those scenes were positioned on flat terrain.

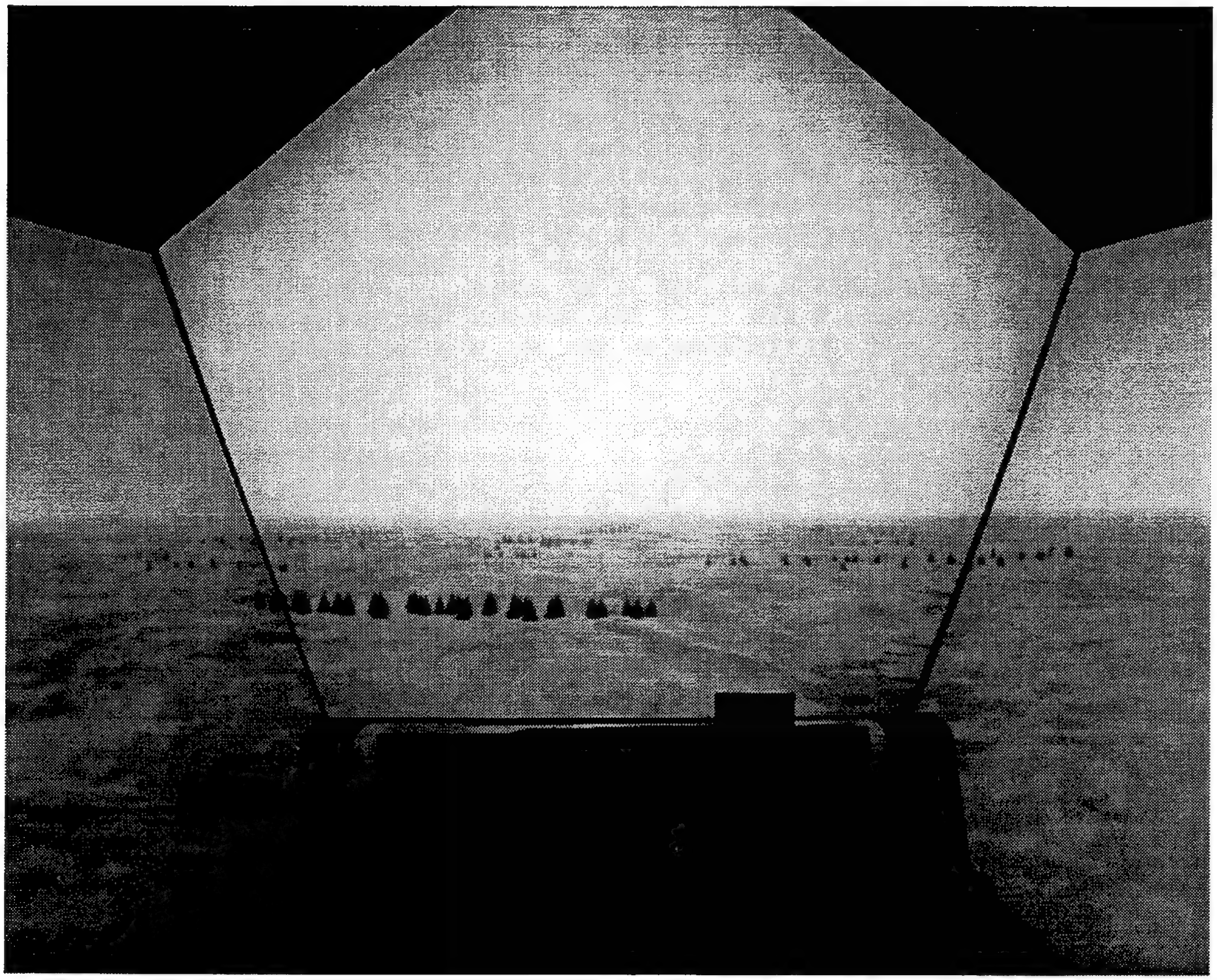


Figure 4.
Scene with Dense Hills and Grouped Trees.

Lack of evidence for systematic differences among subgroups within the sample is consistent with the finding of Kleiss (1992) that dimensional structure with images of real-world scenes was similar between a group of nonpilots and a group of F-16 pilots. Present results extend this null effect to computer-generated scenes and argue that skill at visual low-altitude flight does not involve attention to fundamentally different scene properties than would be attended by nonpilots. This is not to say that pilots do not differ from nonpilots as previous experiments reveal that pilots are both quicker and more accurate to detect changes in altitude in flight simulators (Kleiss & Hubbard, 1991). The basis for skill with this task may, therefore, lie in the speed with which perceptual information is processed rather than the type of information that is processed. Pilots may also attend to idiosyncratic cues specific to environments in which they routinely fly. These would not be reflected in results obtained with novel stimuli. On the practical side, it appears appropriate to use nonpilot subjects in future experiments of this sort.

EXPERIMENT 2

The field of view with the three-window display used in Experiment 1 exceeds by a wide margin that used by Kleiss (1990; 1992; In press) with images of real-world scenes. Although displays ranging from 19-inch video monitors (Kleiss, In press) to a large-screen CRT projector (44 deg horizontal field of view, Kleiss, 1992) yielded essentially the same dimensional structure, it is possible that the present three-dimensional structure results in part from the large field of view (210 deg horizontally) used in Experiment 1. To investigate this possibility, it was decided to replicate the experiment using only the center window of the three-window display. This display provides a maximum horizontal field of view of approximately 70 deg which, although larger than any displays used previously with images of real-world scenes, is considerably smaller than the 210 deg horizontal field of view available with the full three-window display configuration.

Method

Subjects

The subjects were six male and four female nonpilots (mean age was 27.8 yr) with normal or corrected-to-normal vision. Nonpilots were used because of lack of evidence for differences between pilots and nonpilots in Experiment 1.

Apparatus

Imagery was displayed on the center (forward looking) pentagonal screen of the display described in Experiment 1. Maximum field of view was about 80 deg horizontally by 70 deg

vertically. A neutral gray field equal in luminance to the sky in stimulus scenes (31.656 Cd/m^2) was displayed in the two side windows. All other aspects of the apparatus were identical to Experiment 1.

Stimuli, Design and Materials

A missing data design was used in Experiment 1 to reduce the number of stimulus pairs presented to each subject. Kruskal and Wish (1978) suggest that 13 stimuli are sufficient to identify up to three dimensions, and Schiffman, Reynolds and Young (1981) suggest that fewer stimuli can be used if sample size is kept to around ten subjects. Given the lack of evidence for greater than three dimensions in Experiment 1, it was decided to reduce stimulus set size from 16 to 12 stimuli yielding a total of 66 stimulus pairs. This number is sufficiently small so that each subject can view all possible stimulus pairs in a single session.

Four scenes were selected for deletion in the following way: First, one of the four scenes with flat terrain was selected. Next, one of the three remaining types of scene elements was then randomly selected from scenes with rolling terrain. One of the two remaining types of scene elements was randomly selected from scenes with sparse hills and the remaining type of scene element was selected from scenes with dense hills. The four scenes selected for deletion were (a) flat with texture and grouped trees, (b) rolling with texture and evenly spaced trees, (c) sparse hills with texture, and (d) dense hills. Stimulus pairs were arranged in two random sequences which differed with respect to the order of scenes in individual pairs. All other methodological aspects of the experiment were identical to Experiment 1.

Procedure

The procedure was identical to that described in Experiment 1.

Results and Discussion

Rating data were analyzed using ALSCAL for PCs. The weighted (individual differences) option was retained because it tends to provide the most reliable results (Schiffman, et al., 1981). Ratings were assumed to be ordinal and continuous. Figure 5 shows 1-RSQ, S-Stress and Stress as a function of increasing dimensionality. Note first that all values are considerably larger than in Experiment 1 (see Fig. 2), particularly those for 1-RSQ. Because fit tends to improve as stimulus set size decreases (e.g., Spence & Ogilvie, 1973), we may conclude that the fit of the data in the present experiment is especially poor in comparison to Experiment 1. There is a hint of an elbow at dimensionality equal to three for 1-RSQ and at dimensionality equal to four for Stress. Because

there is no clear evidence to support any particular dimensionality, a preliminary step in assessing the structure present in these data will be to calculate intercorrelations between stimulus coordinates for the three-dimensional solution in Experiment 1 and the two-, three- and four-dimensional solutions in the present experiment. These are shown in Table 2.

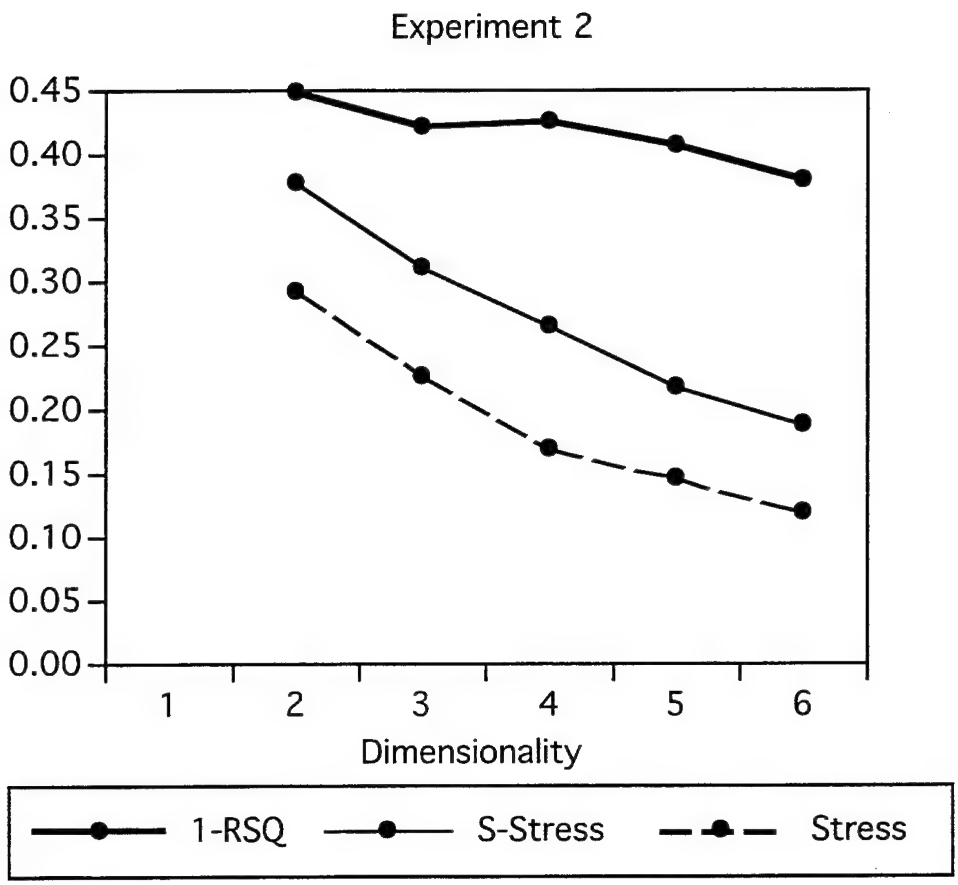


Figure 5.
S-Stress, 1-RSQ and Stress as a Function of Dimensionality: Experiment 2.

Table 2. Intercorrelations between three dimensions in Experiment 1 and two-, three- and four-dimensional solutions in Experiment 2.

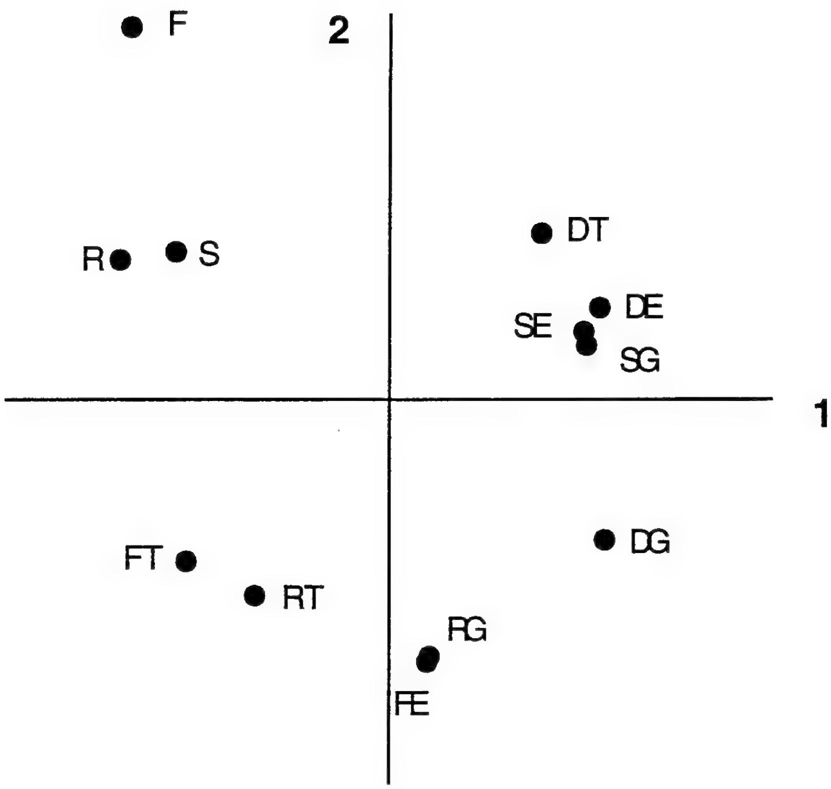
	3 Dimensions (Exp. 1)			2 Dimensions (Exp. 2)		3 Dimensions (Exp. 2)		
	1	2	3	1	2	1	2	3
Experiment 2								
2 Dimensions								
1	.77	-.57	-.70					
2	.60	-.24	.20					
3 Dimensions								
1	-.85	.47	.67	-.96	-.40			
2	-.36	.02	-.67	.16	-.84			
3	.17	-.76	-.06	.42	-.04			
4 Dimensions								
1	-.69	.58	.83	-.97	-.17	.95	-.26	-.33
2	-.65	.23	-.27	-.41	-.51	.41	.56	-.32
3	-.41	.02	-.10	-.02	-.85	.27	.67	.36
4	.07	-.54	.23	.08	.26	.00	-.41	.74

The most notable feature of data in Table 2 is the general lack of relationship between dimensions from Experiment 1 and dimensions from the present experiment. The highest correlations are between Dimension 1 in Experiment 1 and Dimension 1 of the present three-dimensional solution, and Dimension 3 in Experiment 1 and Dimension 1 of the present four-dimensional solution. Clearly, present data do not exhibit structure similar to that in Experiment 1.

Turning then to the present data, note that correlations are particularly high for Dimension 1 across the two-, three-, and four-dimensional solutions. The structure associated with Dimension 1 is, therefore, consistently reflected in all three solutions. In addition, Dimension 2 in the two-dimensional solution is also highly correlated with Dimension 2 in the three-dimensional solution and Dimension 3 in the four-dimensional solution. Coordinates in the three-dimensional solution are not highly correlated with the four-dimensional solution. Given that two dimensions are consistently reflected across all solutions, the two-dimensional solution will be considered.

Figure 6 shows the derived two-dimensional spatial configuration. Considering Dimension 1 first, note that scenes at the left end of the dimension contain no objects or texture, scenes near the middle of the dimension contain trees and/or texture and scenes nearest the right end of the dimension contain steeply sloped hills and trees. This pattern supports an interpretation of Dimension 1 consistent with increase in global scene complexity exemplified by a composite of

scene properties. There is no obvious structure revealed in the positioning of scenes along the Dimension 2 axis. Present data, therefore, may actually be one-dimensional in nature.



F = Flat
R = Rolling
S = Sparse Hills
D = Dense Hills
T = Texture
E = Texture & Evenly Spaced Trees
G = Texture & Grouped Trees

Figure 6
Two-Dimensional Spatial Configuration: Experiment 2.

It is important to note that the failure to obtain interpretable multidimensional scene structure in the present experiment cannot be attributed to a failure to perceive either texture, trees, or hills in scenes. Each is clearly perceived in scenes as is indicated by Dimension 1. They are simply not perceived as being uniquely different from one another. This result shows that some important information in flight simulator visual scenes goes beyond the mere presence or absence of specific scene features. Researchers have argued that information useful for perceiving and controlling one's own motion within an environment is based upon patterns or structural relations in visual stimulation (e.g., Flach, Lintern & Larish, 1990; Flach & Warren, 1993; Lintern, 1991; Wolpert, 1990). An example of structural information that varies with field of view is discussed by Wolpert (1990). Optic flow structure in the direction of heading expands outward from the vanishing point on the horizon whereas optic flow becomes increasingly parallel as regions are sampled at greater eccentricities from the heading direction. Warren and Kurtz (1992) and Wolpert (1990) provide evidence that parallel optic flow is more informative regarding self-motion events than is expanding optic flow (see, however, Crowell & Banks, 1993, for contrary evidence pertaining to perception of heading). Differences in optic flow structure off axis from the heading direction could explain the perceived difference among texture on the terrain (Dimension 1), discrete scene elements (Dimension 2), and terrain shape (Dimension 3) with the wide field of view. Another possibility is that the large field of view provides greater peripheral stimulation of the retina.

The influence of optic flow structure off-axis from the heading direction could be explored by replicating the experiment using a single side window rather than the forward window. Assuming that gaze was directed toward the side window, peripheral stimulation of the retina would be the same as in the present experiment whereas optic flow structure would different. Evidence for multidimensional scene structure in this condition would argue that optic flow structure rather than peripheral stimulation of the retina is the important factor underlying the present advantage for the large field of view. It should be mentioned, however, that evidence of multidimensional scene structure has consistently been obtained with real-world scenes viewed with much smaller fields of view (Kleiss, 1990, In press). Present scenes, therefore, may be lacking in some other type information that is not exclusively related to the side display windows.

GENERAL DISCUSSION AND CONCLUSIONS

The finding in Experiment 1 of a dimension related to objects (Dimension 2) and a dimension related to terrain shape (Dimension 3) is consistent with results of Kleiss (1990, In press) using real-world scenes and provides evidence that subjects were perceiving similar information in simulated scenes. Indeed, identification of a third dimension (Dimension 1) related to presence or absence of texture on the terrain indicates that present computer-generated scenes

contained an even richer variety of information than the real-world scenes used by Kleiss (1990, in press). Dimension 1 was defined by comparisons involving scenes with completely textureless surfaces. This suggests that even the most austere real-world scenes used by Kleiss (1990, in press) (e.g., a calm ocean and a dry lake bed) contained sufficient texture to mask this distinction. The pervasiveness of texture in real-world scenes suggests that terrain texturing capabilities should be considered a requirement in flight simulators.

Although present scenes were found to be rich in visual information perceived in real-world scenes, results point to specific areas in which scenes might be enhanced. Some scene items were related to more than one dimension indicating that subjects were attending to more than one characteristic of the same scene items. For example, a global property of texture was related to Dimension 1 whereas an object-like property of texture was related to Dimension 2. Also, a vertical property of trees was related to Dimension 2 whereas trees facilitated perception of terrain shape in Dimension 3. It is not likely that these different characteristics of texture and trees are optimized in the same scene items. Rather, it is likely that scene items should be rendered differently to optimize each separate characteristic. A prerequisite to optimizing scenes is to identify the specific characteristics of texture and trees that were the focus of attention in present scenes.

Researchers interested in self-motion perception have directed considerable attention to identifying components of texture that influence perception of self-motion. Two major components have emerged, texture elements aligned parallel with the heading direction which isolates the perspective gradient and texture elements aligned perpendicular to the heading direction. Perspective information is particularly useful for perceiving change in altitude (Flach, Hagen & Larish, 1992; Wolpert, 1988). Perpendicular texture isolates the compression gradient which is also useful for perceiving change in altitude (Flach, et. al, 1992). In addition, perpendicular texture provides optic flow and edge rate information useful for perceiving change in speed (Larish & Flach, 1990; Owen, Warren, Jensen, Mangold, & Hettinger, 1981). The texture characteristics reflected in Dimensions 1 and 2 may relate to these two components. In the research cited above, however, texture typically consisted of a simple grid pattern on flat terrain. It is not obvious that such an analysis can be directly applied to complex texture patterns such as the one used in present scenes. A goal for future research should be to identifying the relevant characteristics of complex texture related to Dimensions 1 and 2.

Trees in Dimension 2 and terrain shape in Dimension 3 are uniquely defined by a vertical component. The importance of tree-like objects for simulating low-altitude flight has been demonstrated in several experiments (Buckland, et. al, 1981; Martin & Rinalducci, 1983; Kleiss & Hubbard, 1993). However, no research has specifically attempted to isolate the vertical

characteristics of objects and terrain shape that influence performance during low-altitude flight. Present results suggest extending analyses of visual information useful for perceiving self-motion to include that related to vertical scene items.

Differences in terrain shape were perceived up to the highest density of hills in Experiment 1. This implies that highly contoured terrain should be modeled to a fairly high level of accuracy in flight simulators. Scenes with dense hills comprised approximately 245 triangular terrain polygons per square nautical mile (not including trees). Hence, this level should be considered a minimum. Whether this level is sufficient to capture all perceptually relevant aspects of the terrain remains an open question. However, it is important to note that the present level of polygon density could only be maintained over a very limited region of the database due to CIG processing limitations. A much higher terrain polygon processing capacity would be required to model terrain at the present level of accuracy over a wider area of the database.

Present results revealed that terrain shape was a salient property of stimulus segments. In contrast, dense hills are difficult to discern in the static image shown in Figure 4. This suggests that perception of terrain shape was dominated by dynamic cues. Kleiss (in press) found that dynamic cues were also important for perceiving terrain shape in real-world scenes. However, terrain shape was nonetheless perceived even in still photographs of real-world scenes. Therefore, present computer-generated scenes would appear to be particularly lacking in static cues for perceiving terrain shape. This defined another area of flight simulator visual scene content worthy of further investigation.

Present results are based upon judgments of similarity between scenes. Therefore, the degree to which scene items associated with each dimension affect performance during low-altitude flight remains to be determined. Two scenes used in the present investigation (i.e., flat with texture and flat with evenly spaced trees) are similar to scenes used by Kleiss and Hubbard (1993, Experiment 3) to investigate detection of altitude change in a flight simulator. In that experiment, performance improved significantly when trees were added to scenes that already contained texture. A reasonable prediction is that significant performance differences would also be obtained between scenes spaced more widely in the spatial configuration in Figure 3. A note of caution is advised, however, as combining different types of visual information is not always beneficial. For example, Warren and Riccio (1985) found that transfer of skill at controlling altitude sometimes declined when information was added to scenes during initial training. They argued that certain particularly salient information dominated attention such that learning improved when less salient information was presented in isolation. Future experiments should seek to establish the influence of the various scene items on tasks more closely approximating low-altitude flight.

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